Unveiling the origin of the Unidentified Gamma-ray Sources

Francesco Massaro
in collaboration with
R. D'Abrusco, A. Paggi, G. Tosti, J. Grindlay, H. Smith

Happy Halloween!

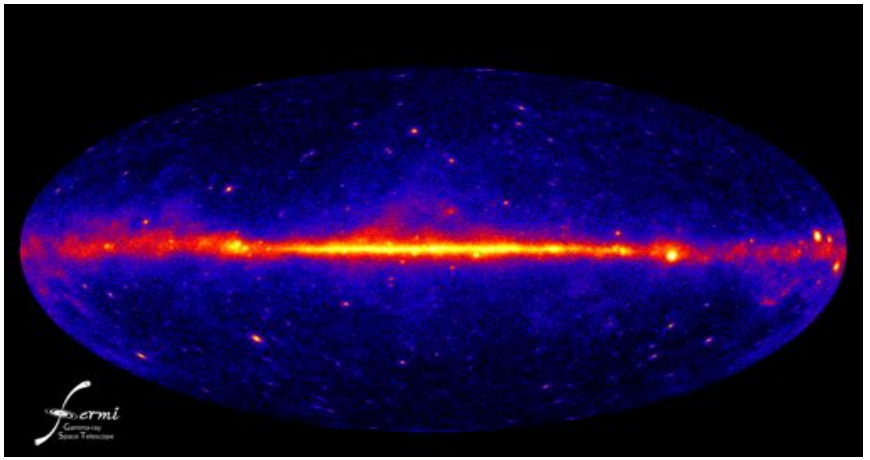
4^{th} Fermi Symposium
Monterey, California

Outline

1. The unsolved mystery of the Unidentified Gamma-ray Sources (UGSs)
2. The blazar phenomenon
3. The discovery of the *WISE* Gamma-ray Strip!
4. A *WISE* method for unveiling the nature of the UGSs
   (see the D'Abrusco talk today at 5.10pm)
5. Selected γ-ray blazar candidates
6. Summary and future prospectives

The advent of the *Fermi* γ-ray satellite

The Fermi Large Area Telescope (LAT) is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV.



The main scientific objectives are:

- To understand the mechanisms of particle acceleration in active galactic nuclei (AGNs), pulsars, and supernova remnants (SNRs).
- Determine the high-energy behavior of gamma-ray bursts and transients.
- Probe dark matter.
- Resolve the gamma-ray sky: unidentified sources and diffuse emission.

The *Fermi* era and the blazar population

The association and the identification of γ-ray sources is improved in the last years

Table 5. LAT 2FGL Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	83	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	25
Pulsar wind nebula	PWN	3	pwn	0
Supernova remnant	SNR	6	snr	4
Supernova remnant / Pulsar wind nebula	...	...	†	58
Globular cluster	GLC	0	glc	11
High-mass binary	HMB	4	hmb	0
Nova	NOV	1	nov	0
BL Lac type of blazar	BZB	7	bzb	428
FSRQ type of blazar	BZQ	17	bzq	353
Non-blazar active galaxy	AGN	1	agn	10
Radio galaxy	RDG	2	rdg	10
Seyfert galaxy	SEY	1	sey	5
Active galaxy of uncertain type	AGU	0	agu	257
Normal galaxy (or part)	GAL	2	gal	4
Starburst galaxy	SBG	0	sbg	4
Class uncertain	...	...	...	1
Unassociated	...	...	...	576
Total	...	127	...	1746

Association table taken from the 2nd Fermi LAT catalog (2FGL) (Abdo et al. 2011).
We cannot talk about γ-ray sources without discuss a bit about blazars.

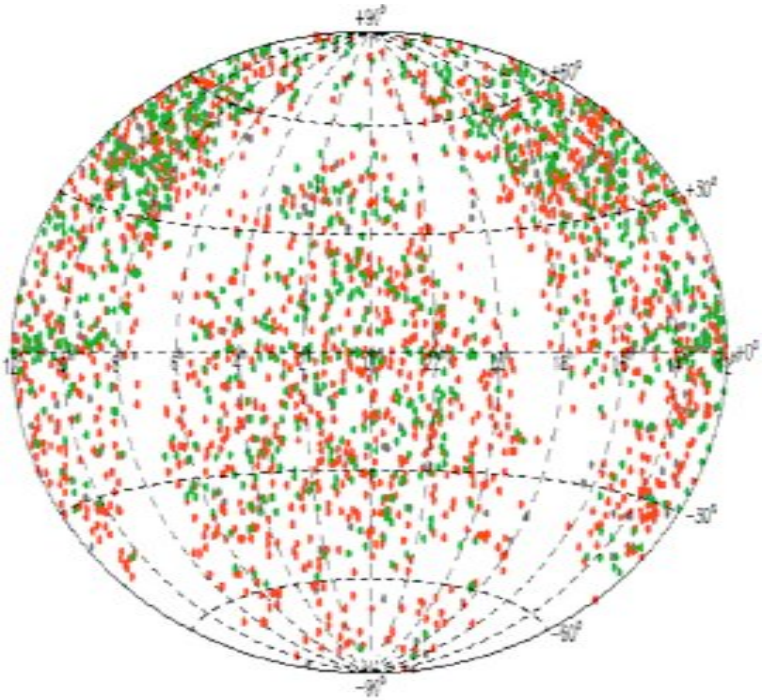
The ROMA-BZCAT

It is a catalogue (i.e., a collection of sources with very similar properties) and it is not a complete sample of Blazars, mostly selected from: radio, optical and X-ray surveys.

✓ Spectroscopically associated at optical frequencies.

Survey name	Blazar type	Survey type	Number of objects	Reference
2 Jansky	BL Lacs+FSRQs	radio flux limited $F(2.7\ \mathrm{GHz}) > 2$ Jy, $\alpha_r \leq 0.4$	60	1, 2, 3
1 Jansky	BL Lacs	radio flux limited $F(5\ \mathrm{GHz}) > 1$ Jy, $\alpha_r \leq 0.5$	34	4
1 Jy NVSS-RASS	BL Lacs+FSRQs	radio, opt, X-ray selection radio fl. limited, $F(1.4\ \mathrm{GHz}) > 1$ Jy	157	5
1 Jy WMAP	BL Lacs+FSRQs	microwave flux limited $F(61\ \mathrm{GHz}) \geq 1$ Jy	180	6, 7
Parkes 0.25 Jy	BL Lacs+FSRQs	radio flux limited $F(2.7\ \mathrm{GHz}) > 0.25$ Jy	371	8, 9
EMSS	BL Lacs	X-ray flux limited $F_X \geq 2 \times 10^{-13}$ erg cm^{-2} s^{-1}	41	10, 11
IPC slew survey	BL Lacs	X-ray flux limited $F_X \geq 2 \times 10^{-12}$ erg cm^{-2} s^{-1}	51	12
DXRBS	BL Lacs+FSRQs	radio+opt+X-ray selection radio fl. limited $F(5\ \mathrm{GHz}) > 50$ mJy	227	13, 14
REX	BL Lacs	radio+opt+X-ray selection	~100	15, 16
RGB	BL Lacs	radio+opt+X-ray selection	127	17
Sedentary	extreme BL Lacs	radio+opt+X-ray selection radio fl. limited $F(1.4\ \mathrm{GHz}) > 3.5$ mJy	150	18, 19
CLASS	BL Lacs+FSRQs	radio+opt $F(5\ \mathrm{GHz}) > 30$ mJy, $\alpha_r \leq 0.5$	147	20, 21
Gamma-ray Blazars	BL Lacs+FSRQs	radio+X-ray selection	241	22
2dF BL Lac Survey	BL Lacs	Optical selection	56 candidates	23, 24
SDSS BL Lac Survey	BL Lacs	Optical selection	347	25
ROXA	BL Lacs+FSRQs+AGN	radio+opt+X-ray selection	816	26
CGRaBS	BL Lacs+FSRQs+AGN	radio flux limited	1625	27
SDSS-FIRST BL Lac Survey	BL Lacs	Optical+radio selection	501	28

(1) Wall and Peacock (1985), (2) di Serego-Alighieri et al. (1994), (3) Urry, Padovani (1995), (4) Stickel et al. (1991), (5) Giommi et al. (2002), (6) Bennett C.L. et al. (2003) (7) Giommi, Colafrancesco, (2004), (8) jackson et al. (2002), (9) Wall et al. (2005), (10) Stocke et al. (1991), (11) Rector et al. (2000), (12) Perlman et al. (1996), (13) Perlman et al. (1998), (14) Landt et al. (2001), (15) Caccianiga et al. (1999), (16) Caccianiga et al. (2002a), (17) Laurent-Muehleisen et al. (1998), (18) Giommi, Menna, Padovani (1999), (19) Giommi et al. (2005), (20) Marchá et al. (2001), (21) Caccianiga et al. (2002b), (22) Sowards-Emmerd et al. (2005), (23) Londish et al. (2002), (24) Londish et al. (2007), (25) Collinge et al. (2005), (26) Turriziani et al. (2007), (27) Healey et al. (2008), (28) Plotkin et al. (2008).



The definition of Blazars in the ROMA-BZCAT has not been chosen on the basis of their infrared properties (Massaro et al. 2009, 2010).

The Blazar observational properties

Blazars are...

- the rarest class of Active Galactic Nuclei (AGNs).
- AGNs with low "intrinsic" luminosity $\sim 10^{42-44}$erg s^{-1}, emitting over the whole electromagnetic spectrum, from radio to γ-ray frequencies.

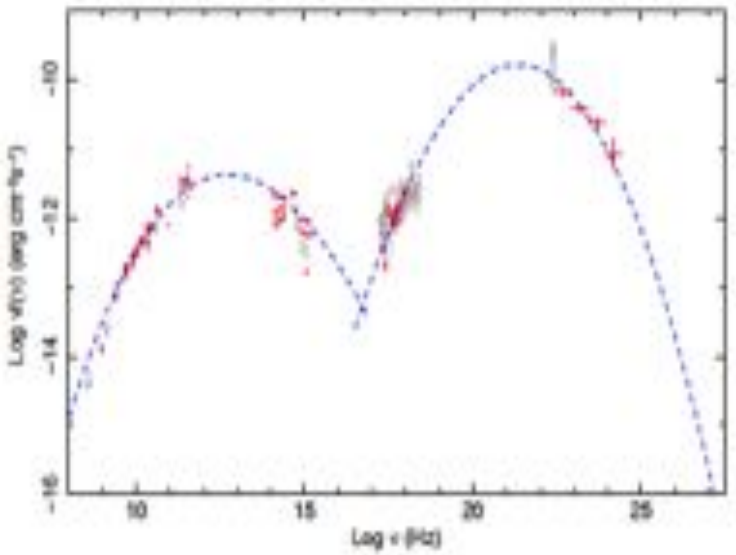
generally showing...

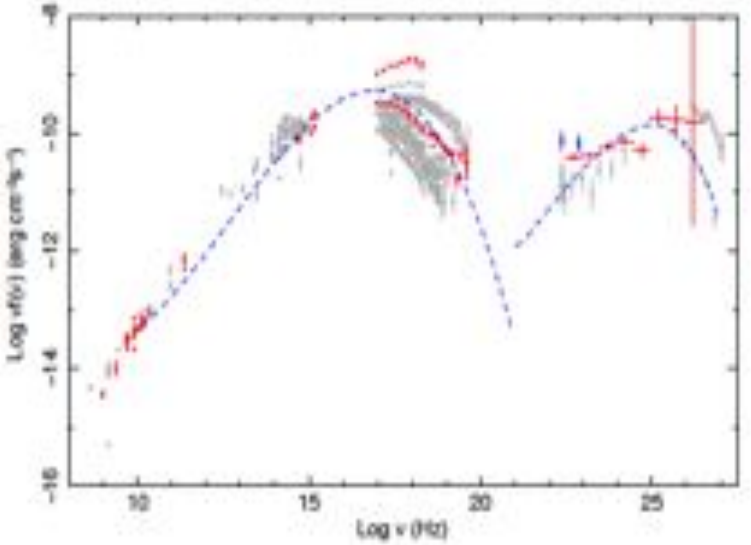
- Weak or absent emission lines in their optical spectra (BZBs).
- Broad emission lines in their optical spectra (BZQs).
- Rapid variability down to 10^2s at every frequency.
- Radio to optical polarization

and ...
they are definitively the largest known class of γ-ray sources not only extragalactic.

The Blazar Spectral energy Distribution

SEDs of 2 bright blazars in the 1FGL (Abdo et al. 2010).



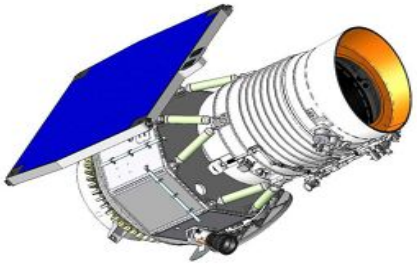


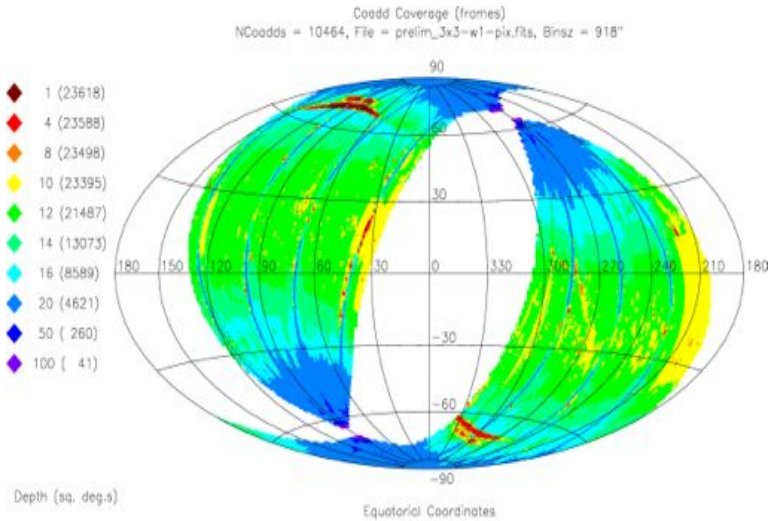
Blazars generally come in two flavors (Giommi & Padovani 1995):

- Flat Spectrum Radio Quasars (BZQs) (prominent HE bump + emission lines)
- BL Lac objects (BZBs) (optically featureless)

The infrared sky seen by WISE

The NASA's Wide-field Infrared Survey Explorer (*WISE* ; Wright et al. 2010) observed the sky at 3.4, 4.6, 12, and 22 μm with an angular resolution of 6.1″, 6.4″, 6.5″ & 12.0″ in the four bands, achieving 5σ point source sensitivities of 0.08, 0.11, 1 and 6 mJy in unconfused regions on the ecliptic, respectively.
The absolute (radial) differences between *WISE* source-peaks and *true* astrometric positions anywhere on the sky are no larger than 0.50″, 0.26″, 0.26″, and 1.4″ for the four *WISE* bands, respectively (Cutri et al. 2011).

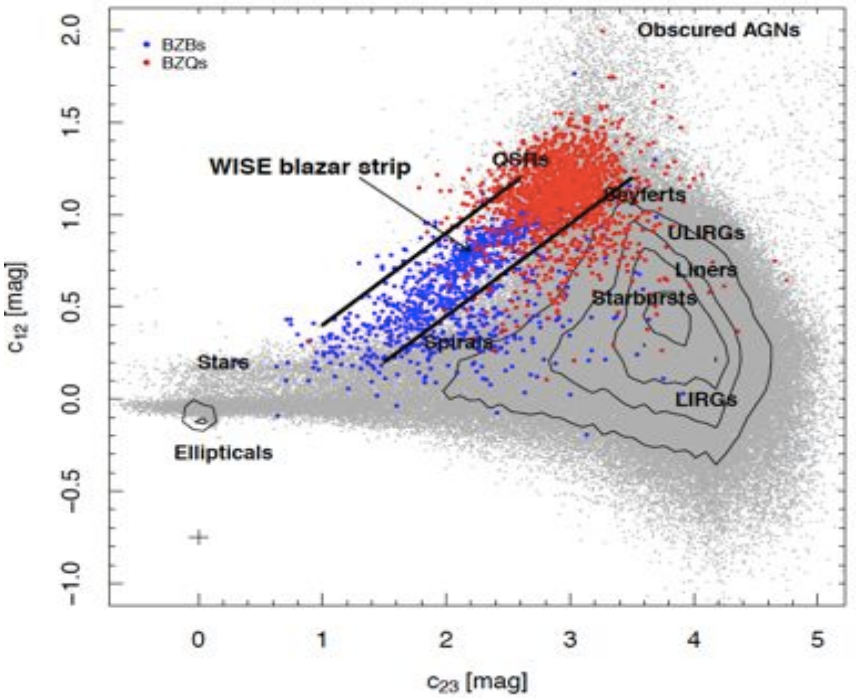


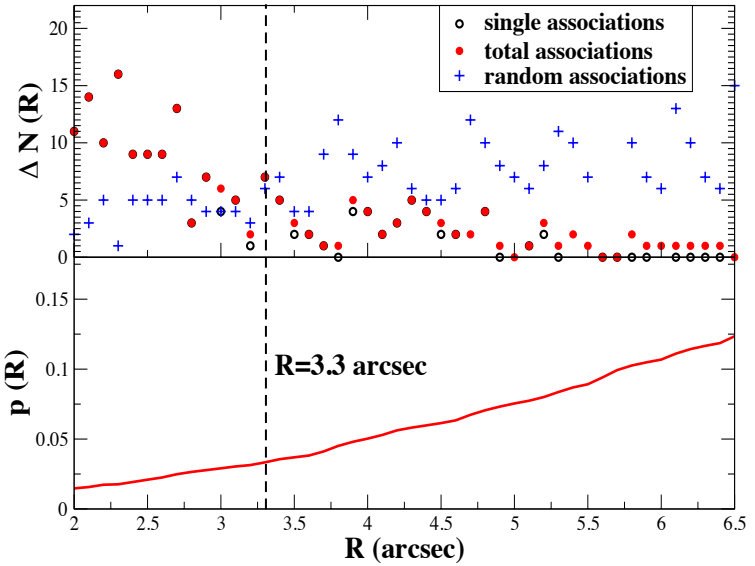


The WISE Preliminary Source Catalog contains the attributes for ∼560 million objects detected on the Atlas Intensity images.

The discovery of the *WISE* blazar strip

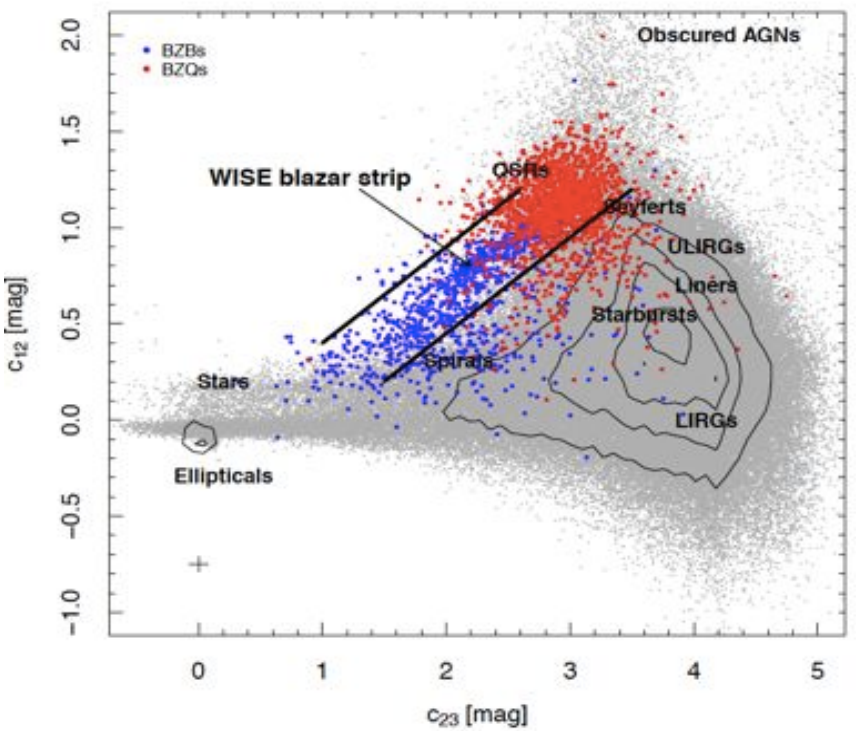
The number ROMA-BZCAT blazars is 3149. The number of positional coincidences within 3.3″ is 3062 (96.3%) detected with a p-chance of 3.3% (only 2 multiple matches!) (D'Abrusco et al. 2012).

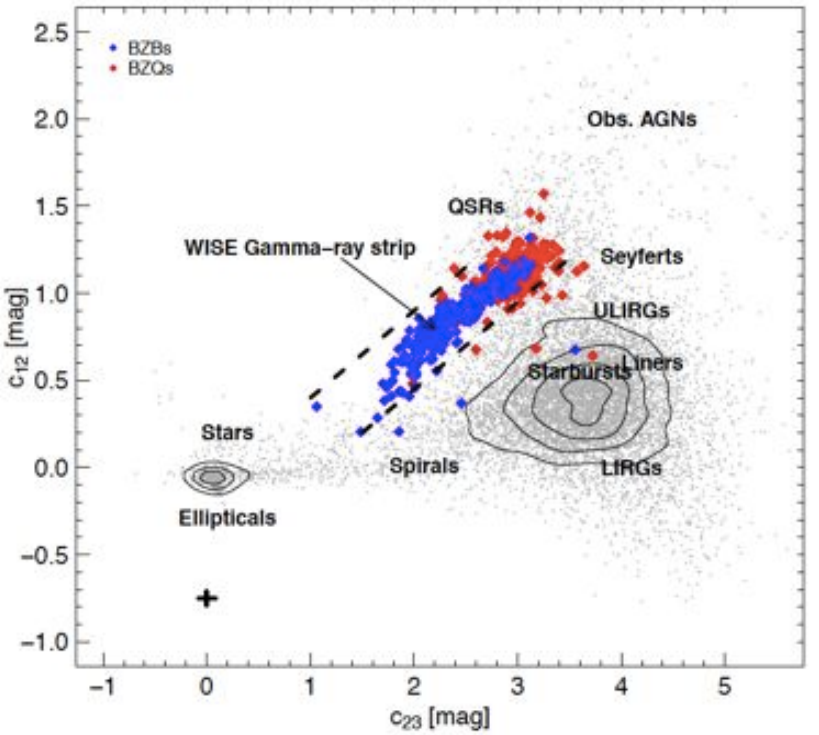




Restricting the *WISE* blazar strip to the γ-rays

The blazar region on the IR color color diagram appear to be narrower.
It is possible to identify the "*WISE* Gamma-ray Strip (Massaro et al. 2012).

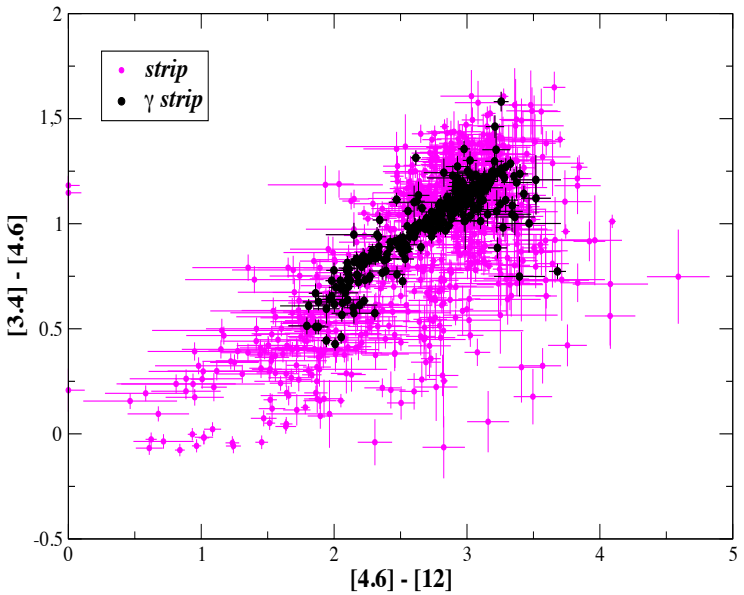


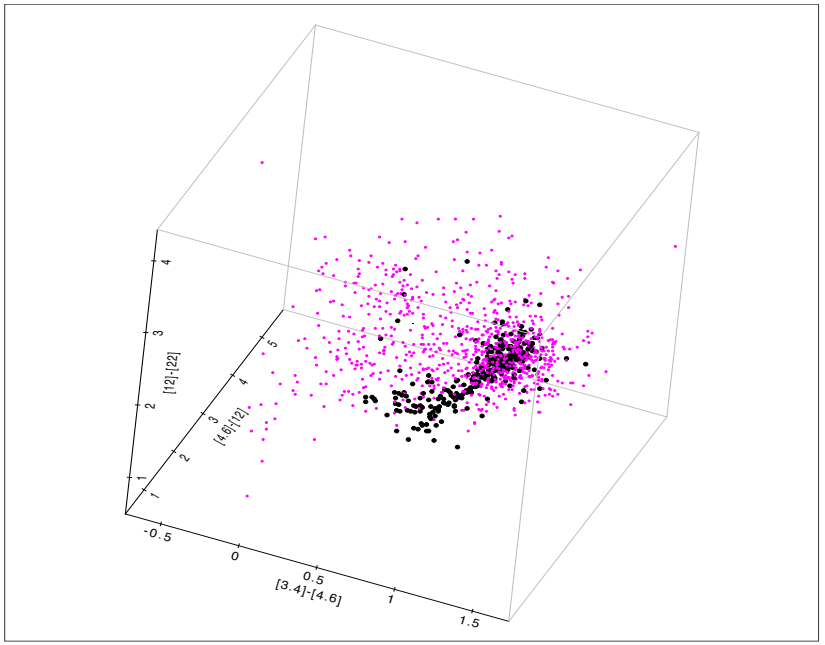


Among the 3032 selected blazars, only 673 have a counterpart in the γ-rays according to the 2LAC (Ackermann et al. 2011); 94.7% are detected in all four *WISE* bands. Then excluding those of Uncertain type: 610 blazars define the *WISE* Gamma-ray Strip (WGS).

The 3D view of the *strip*

Using all the infrared colors from the *WISE* all-sky catalog.





The black points are the blazars that are detected by *Fermi* associated with a *WISE* source while the purple points are those in the ROMA-BZCAT with a counterpart in the *WISE* Catalog (Massaro et al. 2012).

See also the D'Abrusco talk today at 5.10pm for technical details.

A sanity check on the γ-ray blazars

Our procedure re-associates 91% of the γ-ray blazars that belong to the *WISE* Gamma-ray Strip.
- [2FGL - ROMA-BZCAT with a counterpart in *WISE*, detected in all four IR bands.]

All the γ-ray blazar candidates selected according to their *WISE* IR colors are divided in 3 classes (A, B, C).

The *WISE* objects of class A are the most probable blazar counterpart of the unidentified γ-ray sources, because their *WISE* colors are more consistent with the *WISE* Gamma-ray Strip in both the BZBs and BZQs subregions than the colors of sources of class B or C.

See also the D'Abrusco talk today at 5.10pm for additional details.

Advantages with respect to the 2FGL:

- First time using the infrared frequencies (complementary)
- We can apply our method all sky (no need other data)
- The associated counterpart has an error on the position of about 1 arcsec (easy followup observations)
- Blazars are very rare also in the IR colors (need a better estimate of how)
- Method based on the physical processes.

Unidentified γ-ray sources

For the first time we have been able to provide a low energy counterpart for the UGSs

- 258 UGSs out of 576 have been analyzed (no FLAGS in the 2FGL)
- 162 UGSs have at least one γ-ray blazar candidate within the positional uncertainty at 99.9% level of confidence.
- 87 have a unique γ-ray blazar candidate selected with the *WISE* colors.
- 75 have a up to 3 γ-ray blazar candidates of different classes.

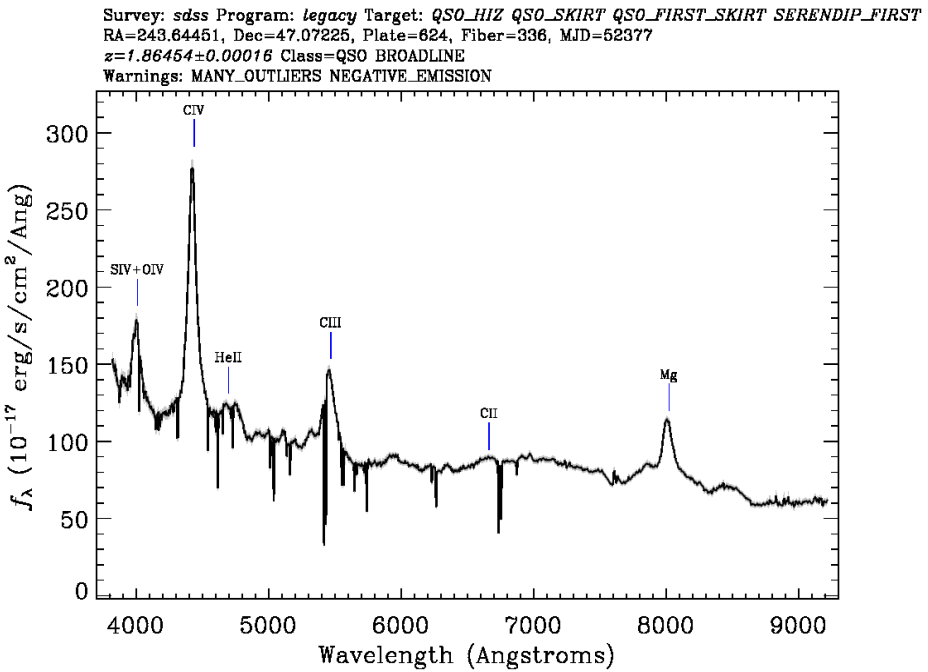
Unidentified γ-ray sources: radio counterparts

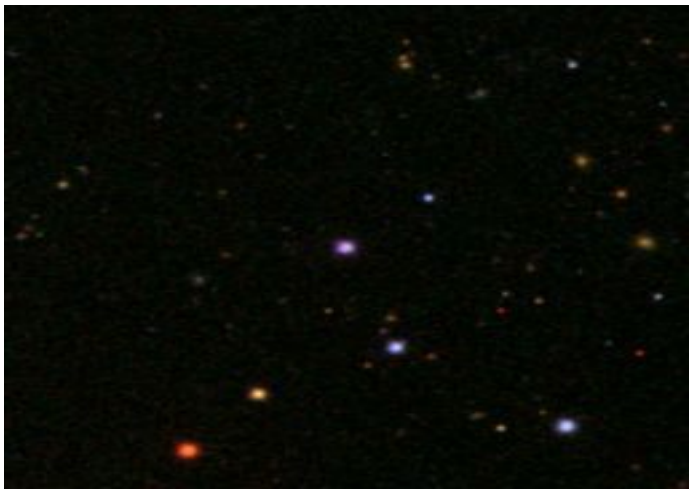
- 17 out of 162 have a counterpart in the radio FIRST survey.
- 39 out of 162 have a counterpart in the radio NVSS survey (12 of them are in the FIRST).
- 40 out of 162 have a counterpart in the radio SUMSS survey (3 of them are in the NVSS).

and ... they are definitively likely to be blazars.

Unidentified γ-ray sources: optical counterparts

- 30 out of 162 have a counterpart in the optical SDSS survey (4 in the FIRST + 4 in the NVSS).
- 27 out 30 sources are classified as QUASARS BROADLINE.
- 3 out 30 sources are classified as galaxies.

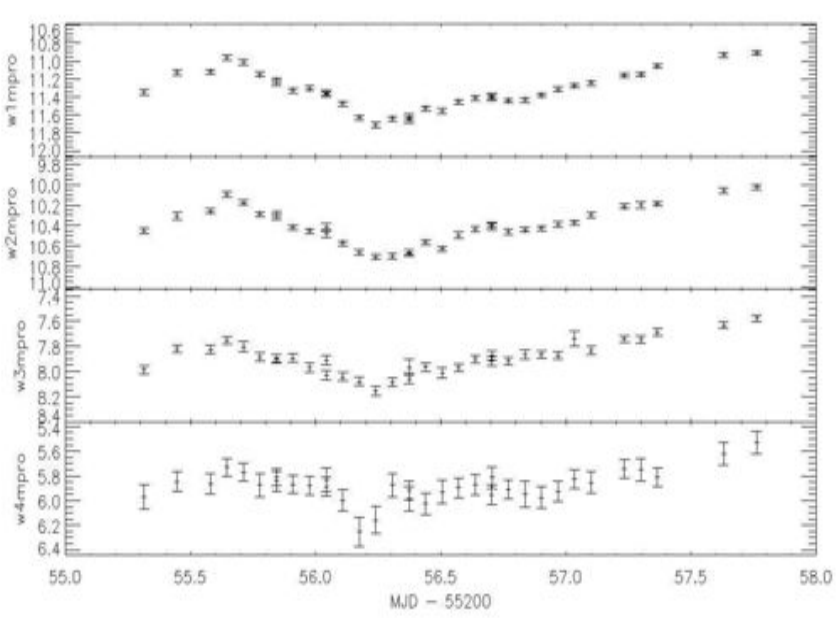


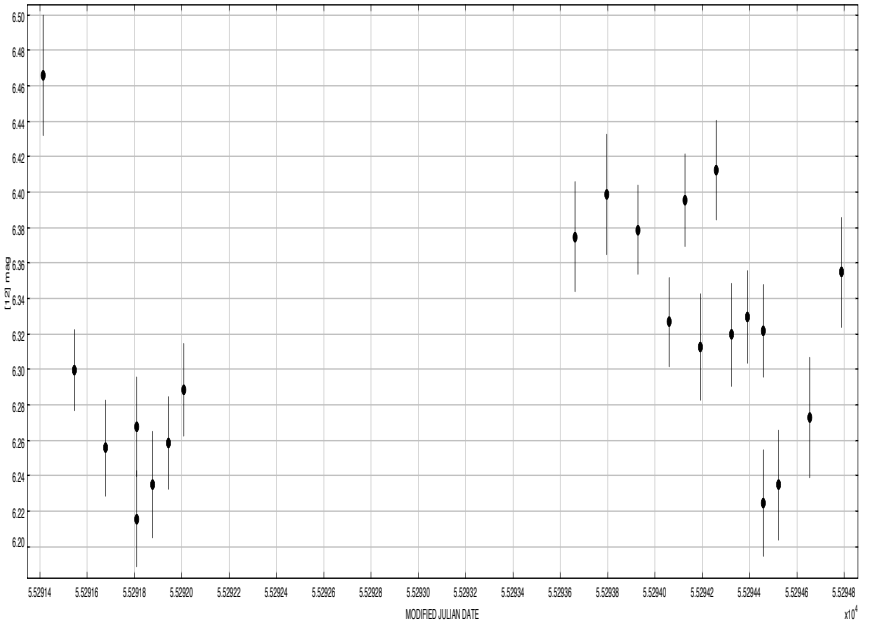


and again ... they are definitively likely to be blazars.

Unidentified γ-ray sources: optical counterparts

- 10% of the γ-ray blazar candidates are variable in the IR. IDENTIFICATION?

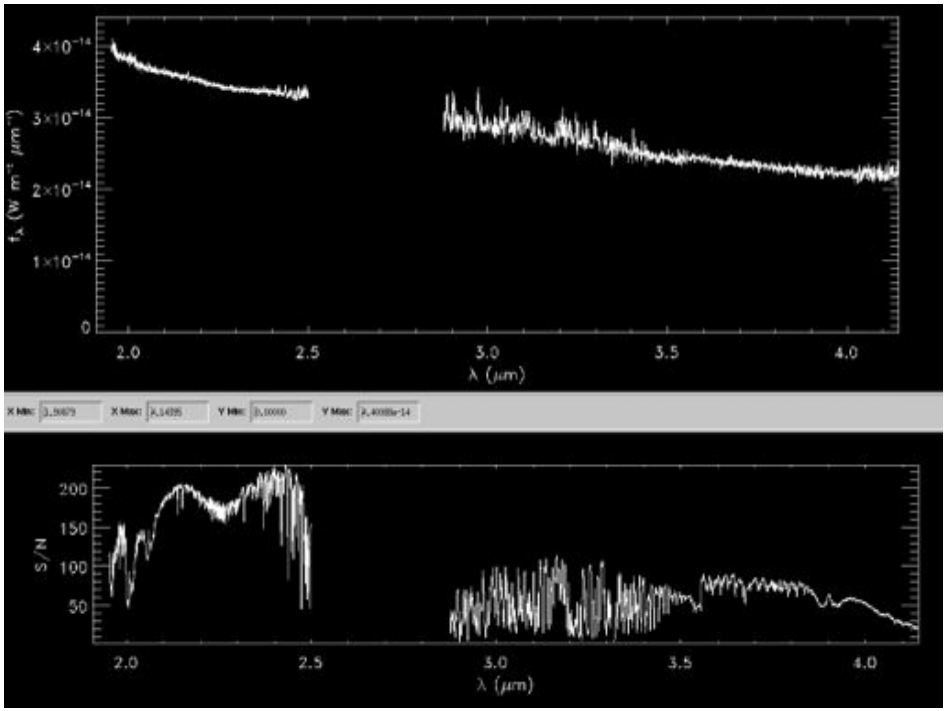




and again ... they are definitively likely to be blazars. This also implies that they cannot be confused with dusty sources.

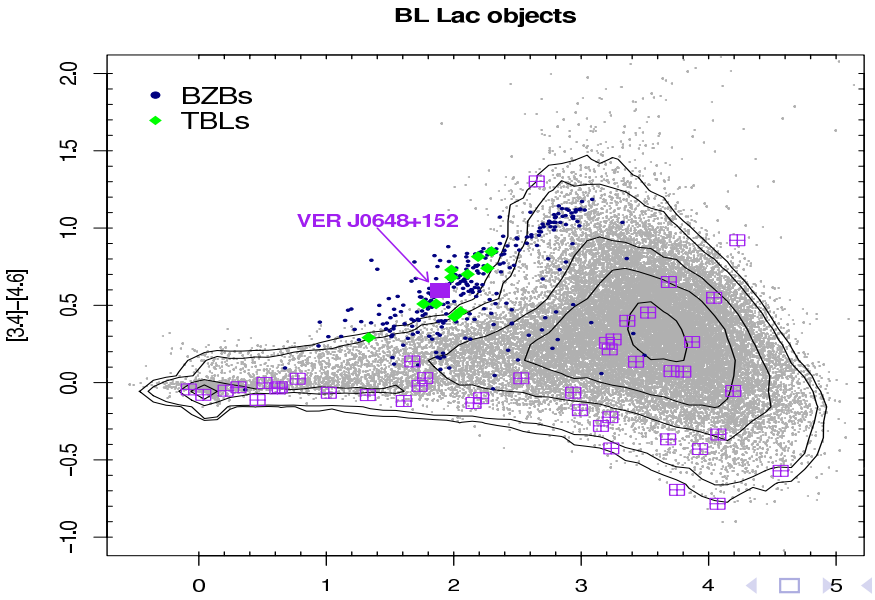
Unidentified γ-ray sources: what are we doing?

1. IR and optical follow up observations
   - proposal submitted to IRTF - MMT - TNG - VLT - NTT (all the sources that cannot be done with a 4mt class telescopes $\rightarrow$ Fermi - NOAO)
2. X-ray follow up observations
   - proposal submitted to SWIFT - XMM - Suzaku



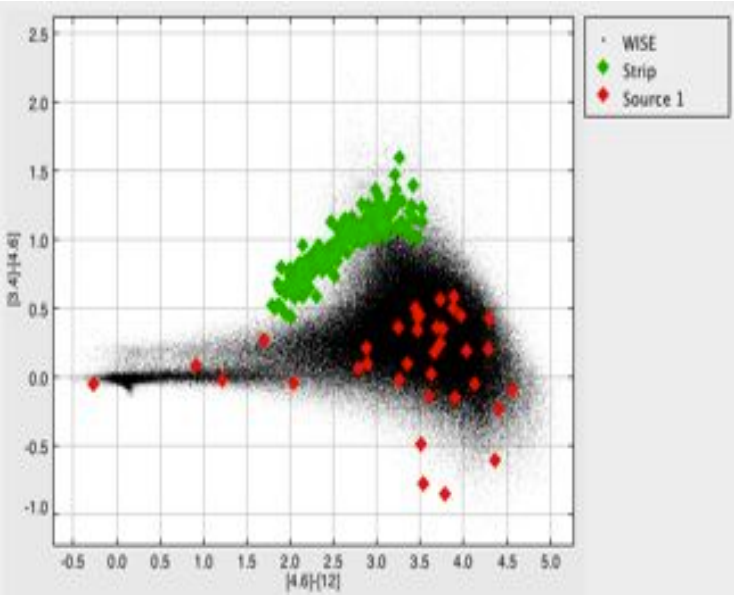
Unidentified γ-ray sources: future prospectives, what are we planning to do?

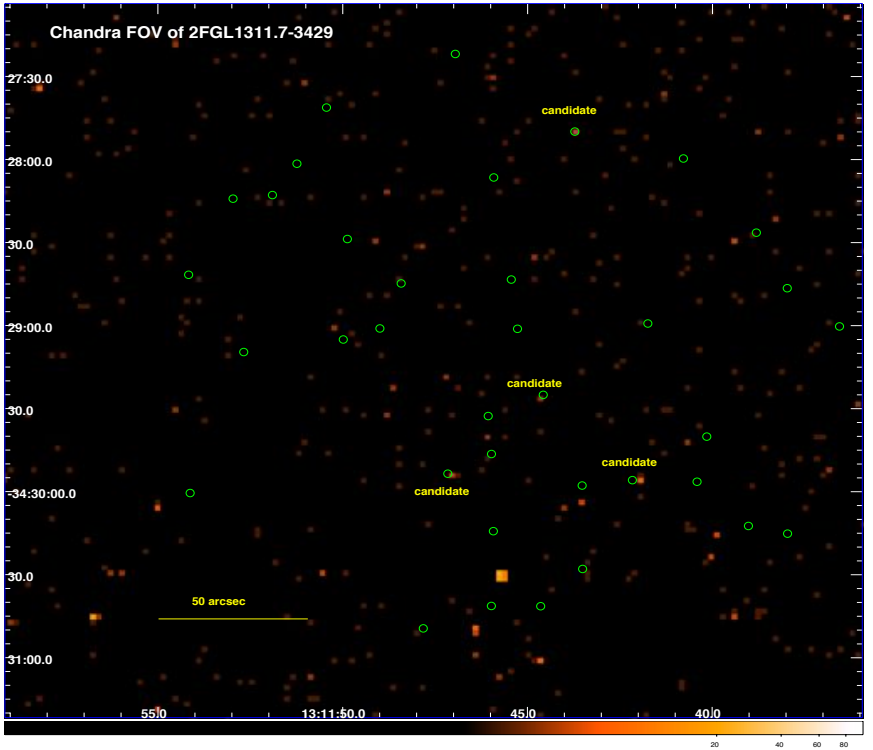
1. Complete optical follow up observations (Fermi - NOAO, 4mt class telescopes) - searching for BL Lacs (featureless spectra) for all the remaining candidates.
2. Complete radio follow up observations (Fermi - NRAO) - do all the blazars have a flat radio spectrum?
3. investigate the X-ray emission of the γ-ray blazar candidates
4. Our method suffers for the TeV BL Lacs (not bright at 22μm) and hard Fermi sources.
5. Dark Matter search list: 2FGL sources without any blazar like counterpart.



The case of 2FGL J1311.7-3429

2FGL J1311.7-3429: α_γ=1.01±0.05 and b=0.2 in γ-rays





1FGL J1311.7-3429 (3EG J1314-3431) is a very bright high-Galactic latitude source, not variable, with a high-energy cutoff in the spectrum very similar to a pulsar. To date, searches for both γ-ray and radio pulsations from this source have been unsuccessful (Ransom et al. 2011).

Summary and Timeline

Main result: the discovery of the **WISE Gamma-ray strip**

We can use the infrared colors of γ-ray blazars to clean the UGSs from those that have a clear blazar candidate associated. AT VERY HIGH LEVEL OF CONFIDENCE!!!

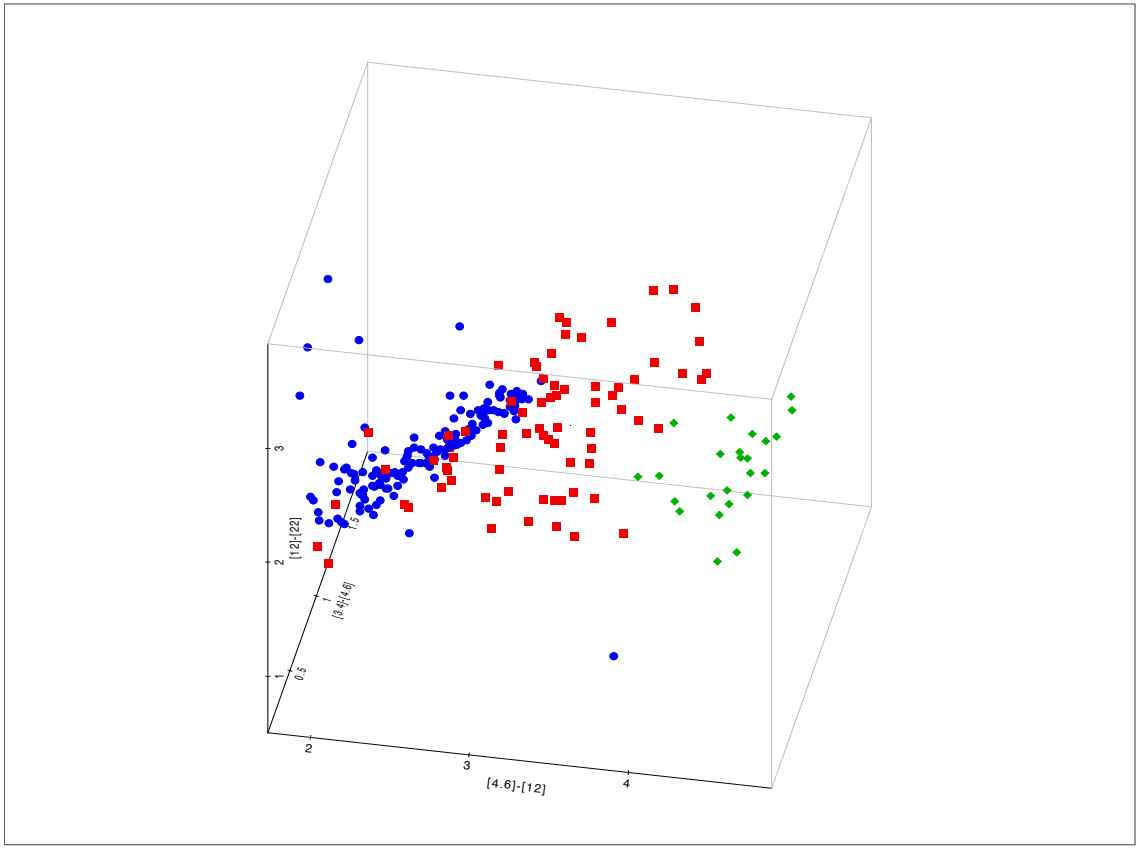
1. The discovery of the WISE blazar Strip [Massaro+11 ApJL published]
2. The characterization of γ-ray blazars in infrared [D'Abrusco+12a ApJ published]
3. Investigation on the nature of the AGUs in the 2FGL sample [Massaro+12a ApJ published]
4. Unidentified γ-ray sources [Massaro+12b ApJ published]
5. Unidentified INTEGRAL sources [Massaro+12c ApJL published]

6. Gamma-ray Blazar Associations [D'Abrusco+12b ApJS in preparation]
7. Radio and optical follow up observations of the γ-ray blazar candidates [Massaro+12d ApJS in preparation]
8. X-ray analysis of the γ-ray blazar candidates [Paggi+12b ApJS submitted]

Thanks!

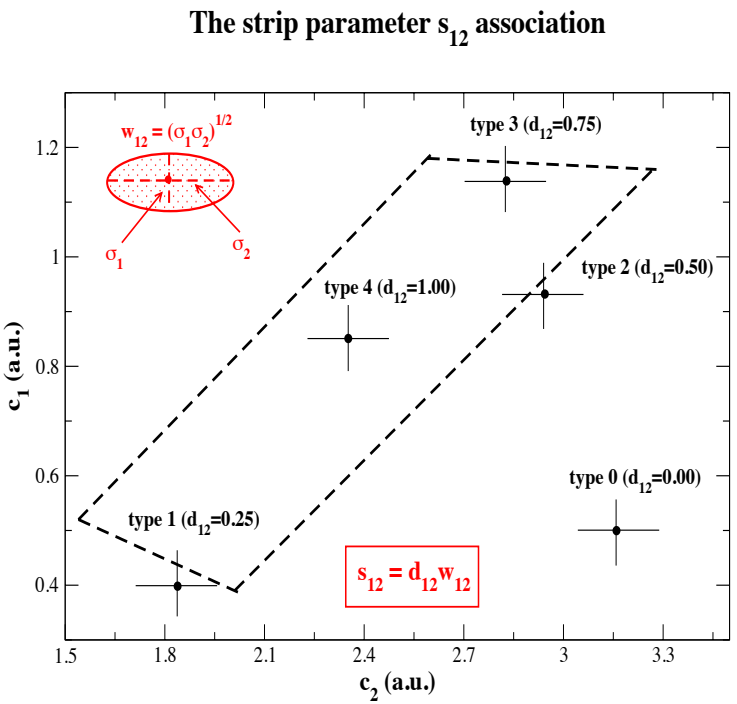
Testing the strip contamination

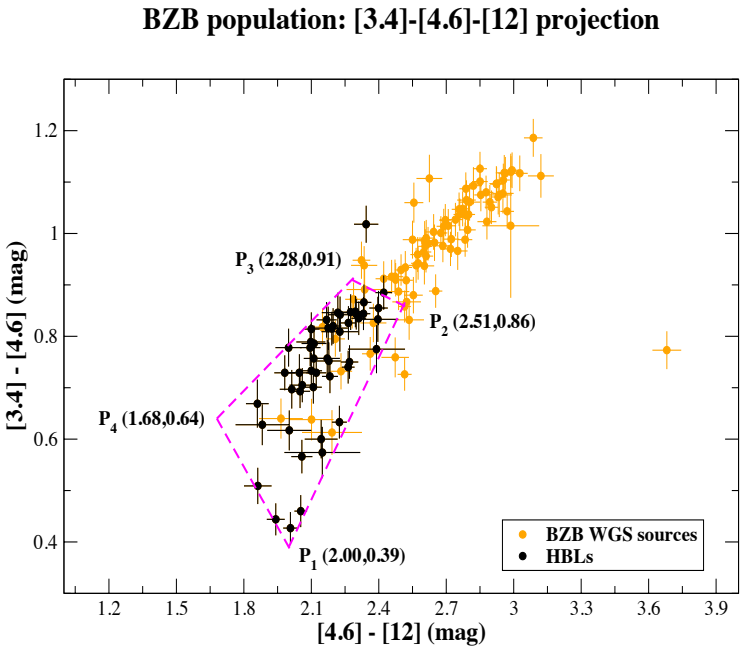
Work in progress... just to give an idea on different γ-ray emitters



- BL Lacs (blue / BZCAT)
- Seyfert type II (red / SWIFT-BAT)
- Starburst Galaxies (green / Weedman et al. 2011)

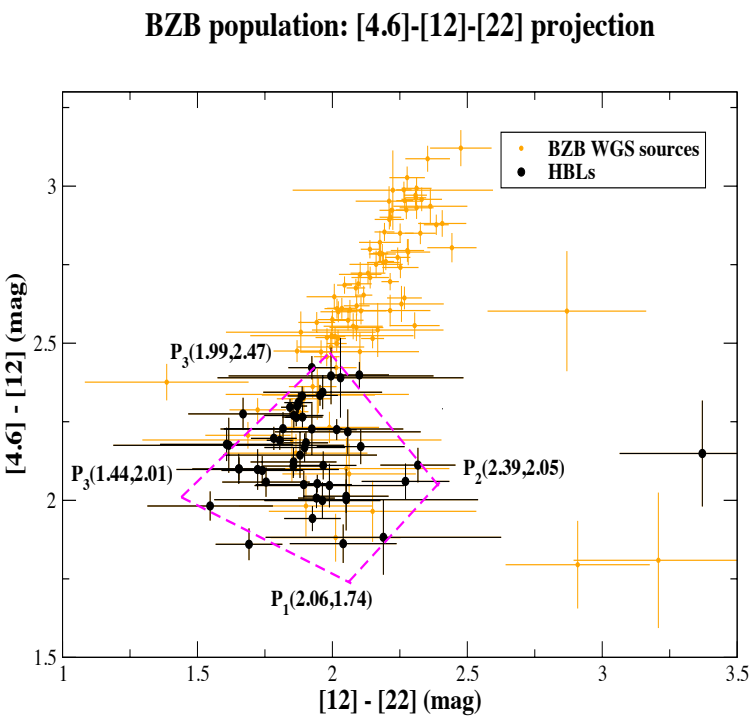
HBLs strip parametrization

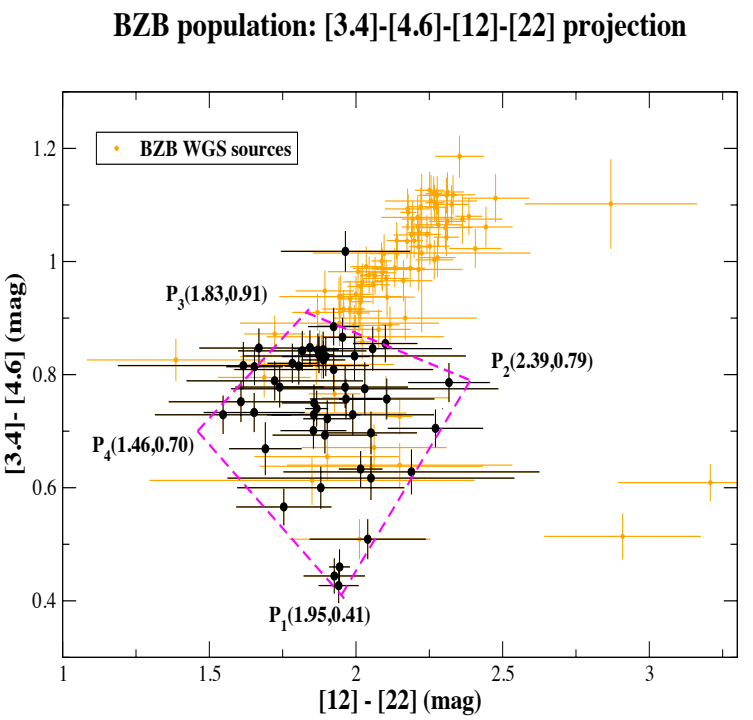




The case the c_1-c_2 2D projection. There are those of *type 4*, that within 1 σ error have all colors on the WGS projection; sources of *type 3* for which only 3 points are within the region of the WGS as well as sources of *type 2* (half points in the WGS) and *type 1* only a single extreme of the errors associated with the WGS. Finally, there are also source of *type 0*, for which none of the extremal point so of the cross lie on the WGS.

Hunting blazars with infrared colors: the strip parameter





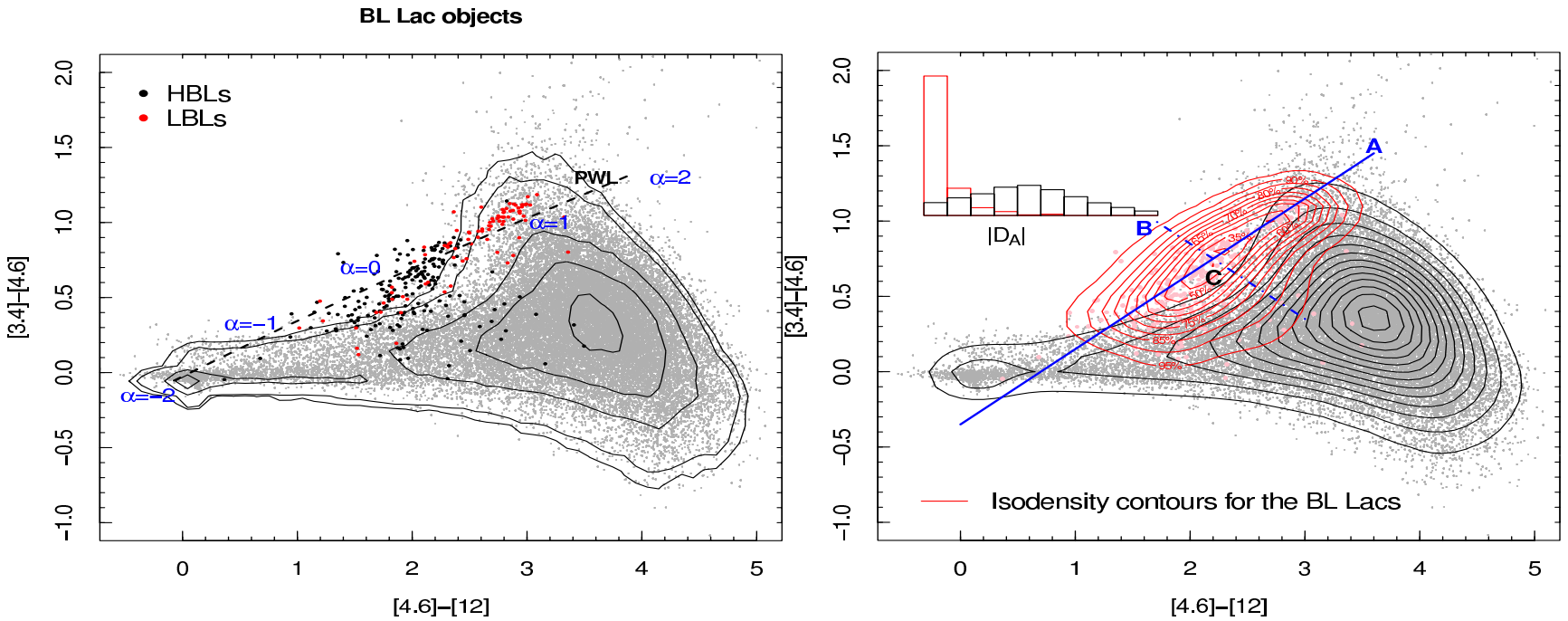
The s parameter values have been used to rank the *WISE* sources and to identify those that could be γ-ray HBL candidates. The s values are normalized between 0 – 1.

Results:

- 581 γ-ray HBL candidates at $|b|$ >20 deg
- 33 are already present in the ROMA-BZCAT (548 are unknown) (all of them!!!)
- 35 are already present in the 2LAC (2 are blazars only according to the 2LAC)
- 36 out of 548 new γ-ray HBL candidates with a candidate radio counterpart (NVSS $8''$)
- *WISE* all sky survey can be extremely useful to find those HBL candidates that we could loose using radio surveys

The properties of the *WISE* blazar strip: the case of BL Lacs

The two subclasses of HBLs (black circles) and LBLs (red circles) are highlighted. We also report the black line correspondent to an IR power-law spectrum of index α (i.e. $S_\nu \propto \nu^{-\alpha}$).



The isodensity contours generated by KDE method. Lines A and B represent the "axes" of the *WISE* strip occupied by BZBs and the directions of maximum gradient of the ratio between probability density of the BZBs to the *WISE* thermal sources. The inset histogram shows the normalized distribution of distances of BZBs sources (red) and *WISE* thermal sources (black) calculated along the line A.

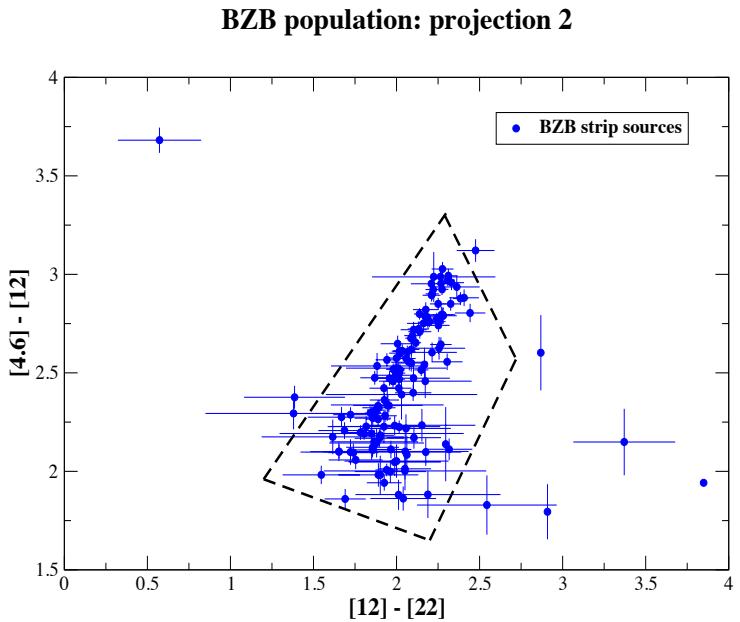
Comparison with the 1FGL unassociated paper

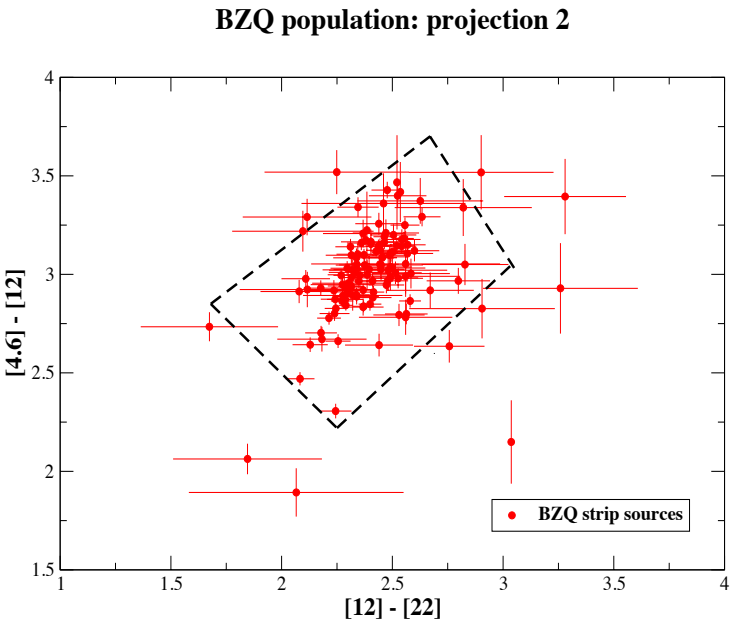
For the first time we have been able to provide a low energy counterpart for the UGSs

- 48 are UGSs for both the 2FGL and the 1FGL, 44 out of 48 are in the 1FGL unassociated paper.
- 27 out of 44 are classified as AGNs (prob. $> 71\%$)
- 17 out of 44 are classified as PSRs (3 prob. $<41\%$ 14 prob. $< 71\%$)
- 10 unclassified.

Hunting blazars with infrared colors: the strip parameter

We combine the values of the s parameters for 3 different projections together to provide a unique value to estimate the source "distance" respect to the WGS.

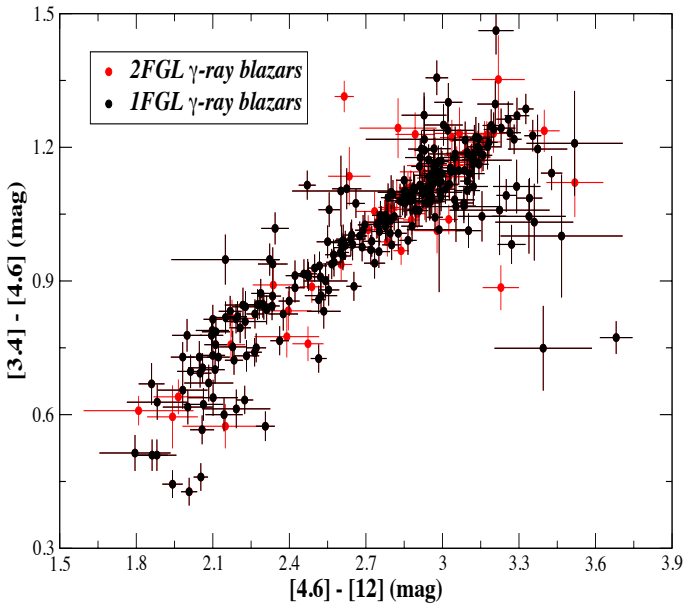


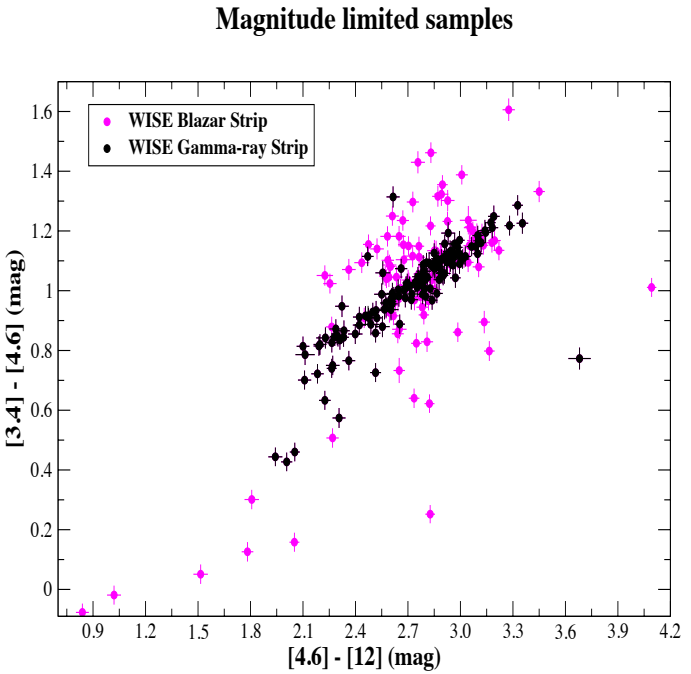


These values have been used to rank the *WISE* sources and to identify those associated with a blazar candidate: The s values are normalized between 0 – 1. We considered one value for BZBs s_b and one value for BZQs s_q.

Possible selection effects: a wonderful referee comment

The 2D projection of the WGS in the IR color diagram [3.4]-[4.6]-[12] μm when only bright γ-ray blazars listed in the 1FGL (black) are considered in comparison with those in the 2FGL (red). There are no clear differences on the thickness of the WGS.





The *WISE* Blazar Strip (magenta) in comparison to the WGS (black) in the IR color diagram [3.4]-[4.6]-[12] μm when only bright IR blazars are considered (i.e., those with *WISE* magnitudes in the ranges: $m_1 \leq 13.5$, $m_2 \leq 12$, $m_3 \leq 11$, $m_4 \leq 7.5$.